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REVIEW ARTICLE

Characteristics and gaps in the assessment of progress in mine restoration: insights from five decades of published literature relating to native ecosystem restoration after mining

Katherine L. Harries[1,2], John Woinarski[3], Libby Rumpff[4], Mark Gardener[3,5], Peter D. Erskine[1]

Desires that mine sites are restored to self-sustaining native ecosystems providing benefits for people have been longstanding. However, achieving and demonstrating progress toward mine restoration goals is complex and requires sustained assessment of numerous disparate components. The recently released Society for Ecological Restoration Mine Site Restoration Standards (SER MSRS) recommend utilizing restoration science assessments to determine whether sites are developing toward similarity with targeted ecosystems and exhibiting self-sustainability. We conducted a global review of publications that assessed restoration to native ecosystems after mining. Our objectives were to (1) document case studies of long-term assessments of mine restoration and (2) evaluate the extent to which restoration assessment has reported the achievement of varied mine restoration goals on a global scale, including (3) whether any ecosystem components and restoration attributes are underrepresented in published assessments. Among the 712 publications we collated, we documented case studies with sustained reporting on similar restoration and significant increase over time in the quantity and breadth of attributes and ecosystems assessed. Nevertheless, notable gaps remain, or underreporting persists. For example, there have been relatively few assessments targeting understanding of key ecosystem processes, resilience, and threats to ecosystem persistence that are necessary for demonstrating "self-sustainability." Our review also revealed limited consideration of ecosystem services that rarely involved impacted communities. We recommend efforts to collate and expand assessments of similar restoration trajectories, placing more focus on indicators that enable the evaluation of characteristics and progress toward a self-sustaining socioecological ecosystem, to help achieve the goals of mine site restoration.

Key words: ecosystem services, function, indicator, resilience, sustainability, trajectory

Implications for Practice

- Comparing published assessment to mine restoration guidelines suggests more attention needs to be directed toward developing indicators and methods for assessing the trajectory of mine site restoration in relation to goals of self-sustaining, resilient ecosystems.
- Assessment of ecosystem services in mine restoration literature is limited. Assessment of whether mine restoration is achieving goals of returning sociocultural benefits should be increased, with more involvement from impacted communities.
- Examples of similar mine restoration with sustained assessment of multiple indicators can be identified. These suggest an evidence base can be built from multiple studies to identify typical mine restoration trajectories that can aid development of indicators for projection of desired outcomes.

Introduction

In many countries, the social license for mining has long been linked to expectations that sites will be returned to a state supporting natural areas similar to previous, or adjacent, ecosystems that return human uses and benefits (Doley & Audet 2016). Similar broad mine restoration goals expressing these expectations have developed in different parts of the world, with associated guidelines and legislative requirements becoming more

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extensive and sophisticated over time (examples are provided in Table S1). Demonstrating achievement of ecosystem restoration, as well as post-closure social benefits, is considered critical for continued community support of mining projects (e.g. Ernst & Young 2022). Therefore, it is important to consider how well the industry can monitor progress toward such restoration goals. This expectation is likely to become increasingly important, with biodiversity and sociocultural impacts of mining within natural ecosystems being predicted to rapidly increase in coming decades (Lèbre et al. 2020; Owen et al. 2023).

However, mine restoration monitoring that can evaluate progress toward, and demonstrate achievement of, self-sustaining ecosystems returning desired human benefits is challenging and requires sustained and sophisticated assessment. This is because restoring native ecosystems to recreate post-mine landforms is challenging and may take much time, and because restoration assessment is part of guiding adaptive management and regulatory decisions around mine closure.

Monitoring programs need to provide evidence to stakeholders that restoration trajectories (patterns over time in measured indicators) will achieve desired attributes, even though these may not be evident within typical mine closure time frames. Ideally, desired attributes and indicators will have been articulated (along with undesired potential deviations) prior to restoration, so that trajectories can be projected and monitored through time. Typically, early assessments focus on the development of substrates because initial processes of remediation to create a safe, stable, and nonpolluting landform provide the foundation for reestablishment of soil processes that can support native plant communities and fauna habitat (Walker & Del Moral 2009). Later indicators focus on whether ecosystem structure, composition, and functions have developed that are similar to targeted ecosystems. However, such similarity may take decades to centuries to achieve (Macdonald et al. 2015; Moreno-Mateos et al. 2020). A self-sustaining ecosystem that will not require ongoing management must not be threatened by factors like invasive weeds and have developed resilience to expected natural and human disturbances (Cowan et al. 2021). Assessments of restoration should therefore be able to demonstrate that soil substrates are developing which will eventually support desired ecosystem diversity, that appropriate similarity in structure and composition has been established, or can develop, and at the very least, that plant and fauna communities are able to persist and reproduce within restored areas, even after disturbance (i.e. are "self-sustaining"). At the point of mine closure, regulatory requirements may require evidence that trajectories can confidently be considered to be trending toward desired outcomes, and that there is an identified plan to mitigate risks of not reaching the desired end state (e.g. ERA 2020).

The recently released Society for Ecological Restoration (SER) International principles and standards for the ecological restoration and recovery of mine sites (Mine Site Restoration Standards [MSRS]) provide guidance about adequate assessment of mine site restoration, addressing the challenges and inherent uncertainty in projecting sustainable desired trajectories (Young et al. 2022). These include recommendations for monitoring of restoration trajectories over long periods using multiple indicators of change from different ecosystem components across many sites (i.e. "multiple lines of evidence"). Ideally data from monitoring these attributes in native ecosystems are used to build a reference ecosystem model than can be used as the basis for monitoring progress toward the desired end state (Young et al. 2022). Attributes that monitoring might compare in reference models and restored mine sites are summarized in a mining specific restoration assessment wheel (Fig. 1) and include considering similarity in ecosystem structure and composition, and whether functions like recruitment, ecosystem resilience, and an absence of threats to continued ecosystem development are present that are particularly important for demonstrating the goal of a self-sustaining ecosystem that will not require ongoing management (Fig. 1).

Whether ecosystems will return desired sociocultural benefits requires separate consideration and should involve community stakeholders (ICMM 2006; Rosa et al. 2020). Ecosystem services are increasingly suggested as relevant to assessing desired social benefits from mine restoration (Rosa et al. 2019; Zhao et al. 2020). In addition, benefits to people from mine restoration may not only include the attributes of ecosystems themselves (like timber or watershed protection), but also the benefits associated with people's involvement in planning and implementing restoration activities. These "well-being outcomes" may be considered part of restoring the "cultural values" of ecosystems (Fig. 1; Young et al. 2022).

Mine site restoration assessment has not been systematically reviewed on a global scale to evaluate whether key factors for understanding, supporting, and projecting desired and sustainable mine restoration are being monitored, resulting in a limited capacity to evaluate whether mine restoration goals are being met, or to highlight characteristics that are least represented and hence require further investment. Mine restoration is often assessed within "gray literature" because it is contained within mining company reports that are rarely publicly available. However, mine sites assessed by researchers within academic institutions and publications arise from mining industry conferences. There have been some recent reviews of this mine rehabilitation literature but these have focused on describing the development of rehabilitation techniques (Bruno Rocha Martins et al. 2020) and technologies (McKenna et al. 2020) and the inadequacy of assessment of fauna (Cristescu et al. 2012; Cross et al. 2019; Lawer et al. 2020). Reviews of the ecosystem restoration literature more broadly highlight that a limited suite of attributes are often reported on, with poor coverage of ecosystem function (Ruiz-Jaen & Mitchell Aide 2005; Wortley et al. 2013; Kollmann et al. 2016). However, these reviews suggest that restoration assessments may build up an understanding of restoration trajectories through compilation and analysis of assessments of similar restoration over time (Ruiz-Jaen & Mitchell Aide 2005). It is likely that collating published assessment of similar mine restoration trajectories, especially from sites with sustained sampling effort, may contribute both to understanding of typical trajectories and the adequacy of assessments in demonstrating and projecting outcomes. Building regional knowledge of mine restoration trajectories has been suggested as important and there are examples of sites where typical restoration trajectory stages

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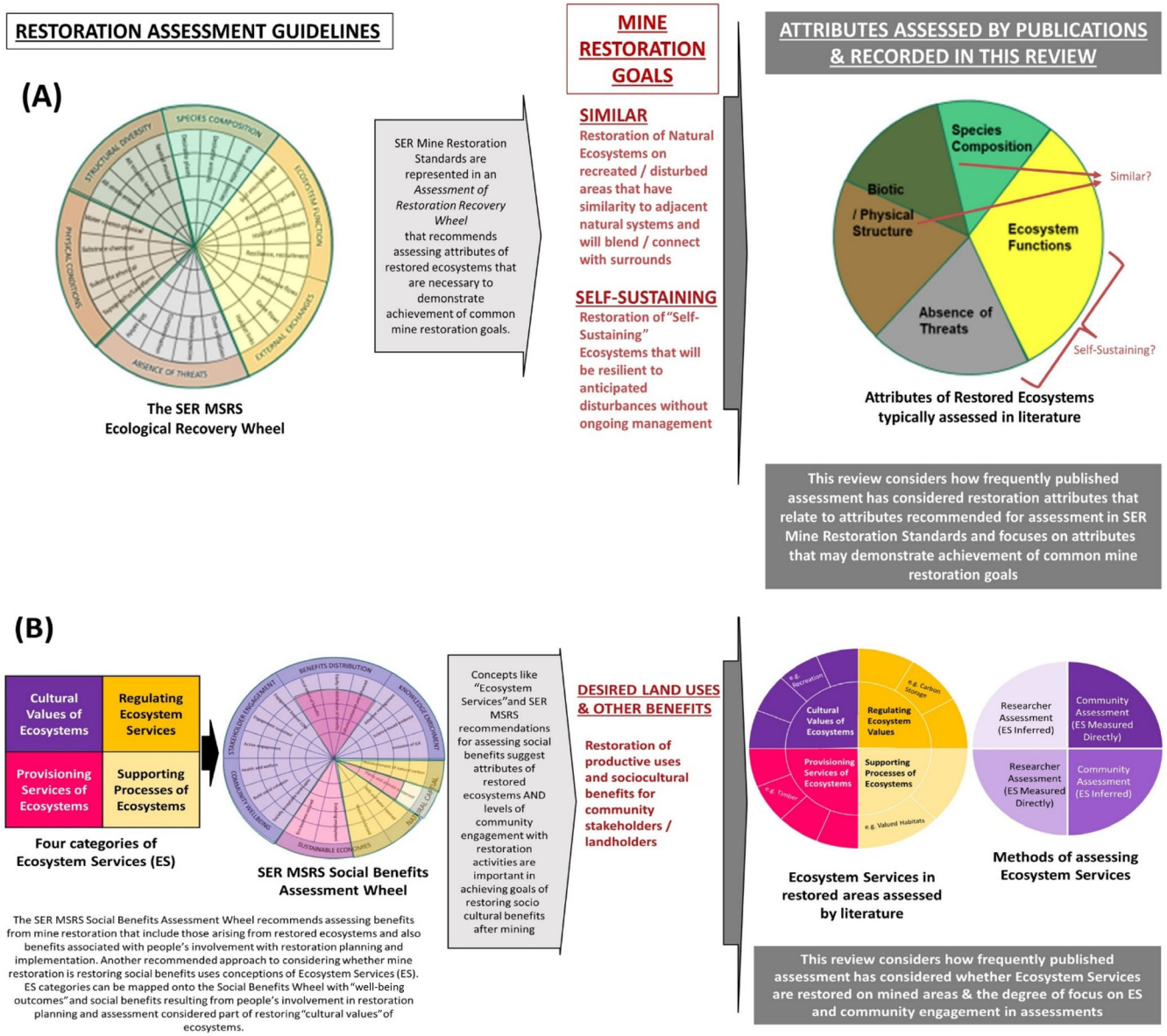

Figure 1. Pictorial representations of restoration assessment guidelines pertaining to common goals for restoring (A) ecosystems and (B) ecosystem services and other benefits to mine sites, linked to attributes assessed by mine restoration literature that are described in this review.

have been described and aided projection and closure decisions (Grant 2006; Young et al. 2022). However, the degree to which this occurs globally is uncertain.

The goal of this study is to collate, describe, and evaluate published assessments of restoration to native ecosystems after mining, specifically to evaluate the capacity of typical assessments to demonstrate achievement of mine restoration goals. A comprehensive review of academic literature targeting assessments of native ecosystem restoration after mining was undertaken to:

(1) Identify the extent and comprehensiveness of monitoring of restoration attributes (for different ecosystem components) identified as important in the SER MSRS.

(2) Evaluate the degree to which published assessment supports evaluation of trajectories with respect to key restoration goals by examining the frequency and comprehensiveness of assessment of:
   - Restoration of functions (particularly nutrient cycling and recruitment) necessary for demonstrating development of a self-sustaining ecosystem; and
   - Restoration of ecosystem services documenting return of social benefits (including whether this involves knowledge or participation of stakeholders).

(3) Identify locations where restoration trajectories have been documented extensively in literature by multiple studies using multiple lines of evidence over long periods. Such long-term studies might provide examples of best-case

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assessment and illuminate how mine restoration assessments are typically assessing and projecting sustainable desired trajectories.

Methods

Selection and Classification of Published Literature

Potential mine restoration assessments were identified through a database search of the published literature from 1970 to 2021 (Fig. 2), to identify assessments of mine restoration projects that have considered both biophysical and sociocultural aspects of ecosystems. We focused on restoration of terrestrial native ecosystems after deep open cut and shallow surface mining (i.e. excluding underground mining). The reviewed literature included conference proceedings, but it was not possible to explore unpublished company reports comprehensively or consistently. Non-English language publications were considered where information had been translated.

Case studies of sustained trajectory assessment included those with multiple (more than 15) published long-term (over 20 years) assessments of similar restoration. Similarity was considered both in terms of the broad type of mining activity (e.g. deep open cut) and the ecosystem being restored. Studies monitored multiple ecosystem (and social) components and included studies from both individual operations and from regions where mining assessments considered similar restoration (details in Table S2; Fig. 2).

Data Extraction and Analysis

To capture broad details of restorations (details in Tables S2–S4; Fig. 2), we recorded whether the status of the assessed restoration was "active" (involving substrate amelioration and/or planting/seeding of native plants) or "passive" (where assessment was of restoration of abandoned mines that had been colonized by native species); the age of the restoration (years established); the target ecosystem and ecoregion (as defined by World Wildlife Fund classifications; Olson et al. 2001); the ores mined; the broad mining method (i.e. shallow surface or deep open cut); and geographic location.

From the assessments, we recorded which *ecosystem components* were measured (definitions in Table S2), including biophysical (plants, vertebrate fauna, soils, etc.), social (attitudes, perceptions, actions), and socioecological (e.g. carbon accumulation, monetary value of forest biomass). Social and socioecological measures were assigned to subcategories of ecosystem services (Fig. 1). Ecosystem recovery attributes assessed were assigned to composition, structure, function, and threat categories (Fig. 1; Young et al. 2022). Details for functional attributes (details in Table S4) such as subcategories of nutrient cycling (indicated by factors like nutrient accumulation) and resilience (recovery after disturbances) were noted to evaluate the extent to which assessments considered ecosystem sustainability. As a measure of social involvement, we noted whether assessments were made only by researchers or involved community stakeholders. For ecosystem services, we noted whether assessments involved direct measures (e.g. recreational values ascertained by surveys of recreational users) or indirect, proxy measures (e.g. carbon sequestration estimated from plants biomass). We also captured general details of the restoration assessment, including publication date and author, and the monitoring strategy employed (i.e. whether studies used reference sites and/or repeat longitudinal measures).

Using data extracted from all reviewed studies (counts of consideration of different components, restoration attribute categories, and types of ecosystem services), we analyzed the proportional focus within the reviewed literature on different (1) attributes of ecosystem composition, structure, and function relating to soils, plants, and fauna; and (2) ecosystem services (details in Supplement S1). Our assessments are similar to the SER MSRS ecological recovery wheels for assessing mine sites (Fig. 1) but are intended to show the focus of assessment literature globally. Trends over time were illustrated using frequency histograms of the different components and types of restoration (i.e. ecosystem type after either deep open cut or surface mining).

Analysis of the case studies included a specific focus on projection of desired restoration trajectories (Fig. 2). We considered what methods and indicators were used to make inferences about restoration being on a trajectory toward a desired end state, or a "self-sustaining" ecosystem. We also examined the use of reference sites in supporting evidence, and whether restoration trajectory stages were described using precedence or existing conceptual models (including an understanding of disturbance recovery in native ecosystems).

Results

Our literature review identified 712 published articles assessing restoration to native ecosystems after mining from 54 countries and 13 ecoregions.

Temporal and Spatial Trends in Published Assessment of Mine Restoration

The number of publications fulfilling our criteria increased exponentially (Fig. S1) between 1975 and 2021, with 221 studies published in the 5 years to 2021, compared to only five prior to 1980. The assessment of different ecosystem components has also increased over time (Fig. 3A). Assessments measuring microbiota and landscape scale consideration of plants increased 2- to 3-fold over the 5 years to 2021 (Fig. 3A). There was an increased incidence of assessment of vertebrate fauna in the more recently published studies and vertebrates were considered more frequently than invertebrates in studies published in the decade prior to 2021 (Fig. 3A). The number of published assessments fulfilling the review criteria increased over time for all the considered ecoregions and the diversity of restoration types assessed (Fig. 3B). Most assessment of open-cut mining in literature related to restoration after coal mining in Europe and North America (Figs. 3B, 4, & S2). Published assessment of shallow surface mining restoration was mostly of restoration after bauxite mining in Australia and Brazil (Figs. 4 & S2).

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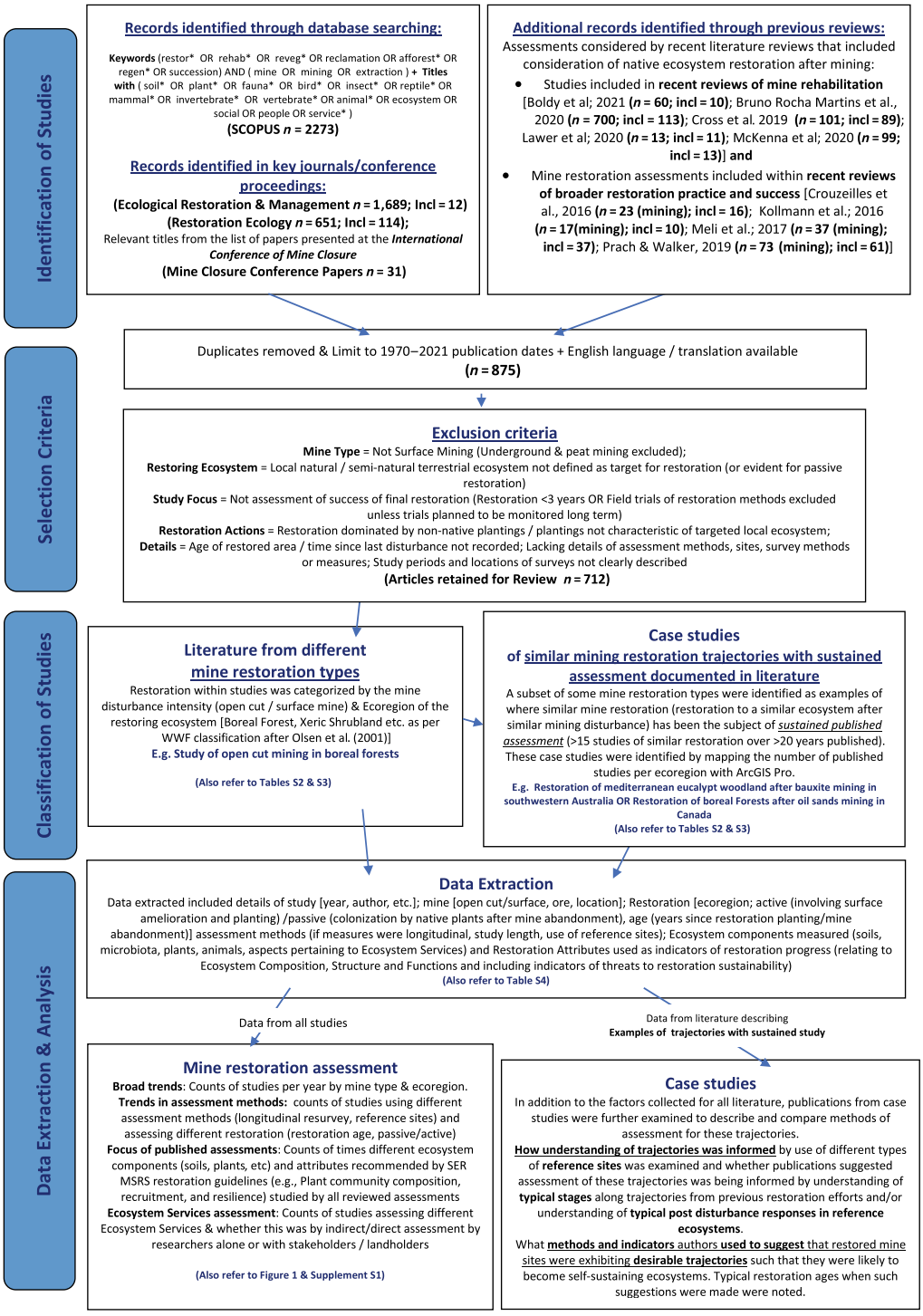

Figure 2. Flow chart describing methodology used to identify, select, classify, extract, and analyze data from published mine restoration studies.

Focus of Mine Restoration Assessments with Respect to Guidelines and Goals

The reviewed mine restoration assessment highlighted plants were the most common ecosystem indicator considered (559 instances/79% of studies), followed by soils (324 instances/46% of studies). Invertebrate fauna was considered more frequently (136 instances/20% of studies) than vertebrate fauna (123 instances/17% of studies), although consideration of vertebrate fauna increased in recent years (Figs. 3A & 5).

The most frequent focus of assessments of soils was accumulation of organic matter/carbon and macronutrients (e.g. N, P, K), which was considered to indicate restoration of nutrient cycling

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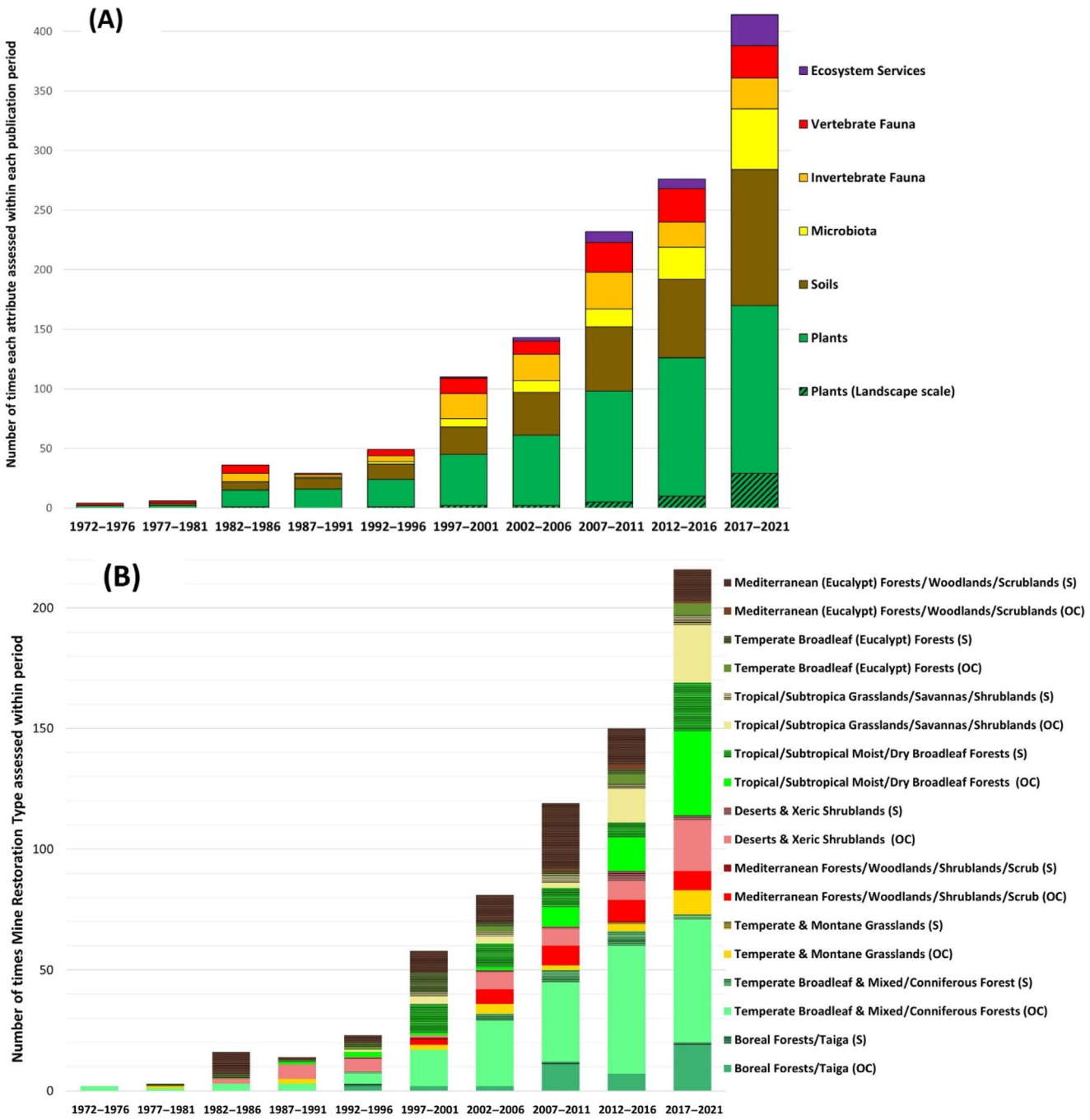

Figure 3. Temporal trends in assessment of (A) ecosystem components and (B) restoration types: The frequency of reporting on different ecosystem components/services and restoration types in assessments of native ecosystem restoration after mining published between 1970 and 2021. Note that studies published prior to 1976 were excluded as they did not satisfy search criteria, apart from one study published in 1975. Refer to Table S2 for definitions of components and restoration types. Legend labels and colors for restoration types match those on the map in Figure 4 with "OC" referring to examples of restoration after deep open cut mining and "S" referring to examples of restoration after shallow surface mining.

functions (265 instances). Activity of soil fauna (20 instances), microbiota (55 instances), and litter breakdown (33 instances) were much less frequently considered as indicators of nutrient cycling. Consideration of threats to the sustainability of soil restoration was infrequent (52 instances) and mostly involved assessment of residual toxicity that might impact biota. Soil structure (e.g. hardness, particle sizes) was considered by around a quarter of the assessments of soils. Many authors suggested soil structure might determine vegetation outcomes but only 11% of studies considering soil structure linked this to plant

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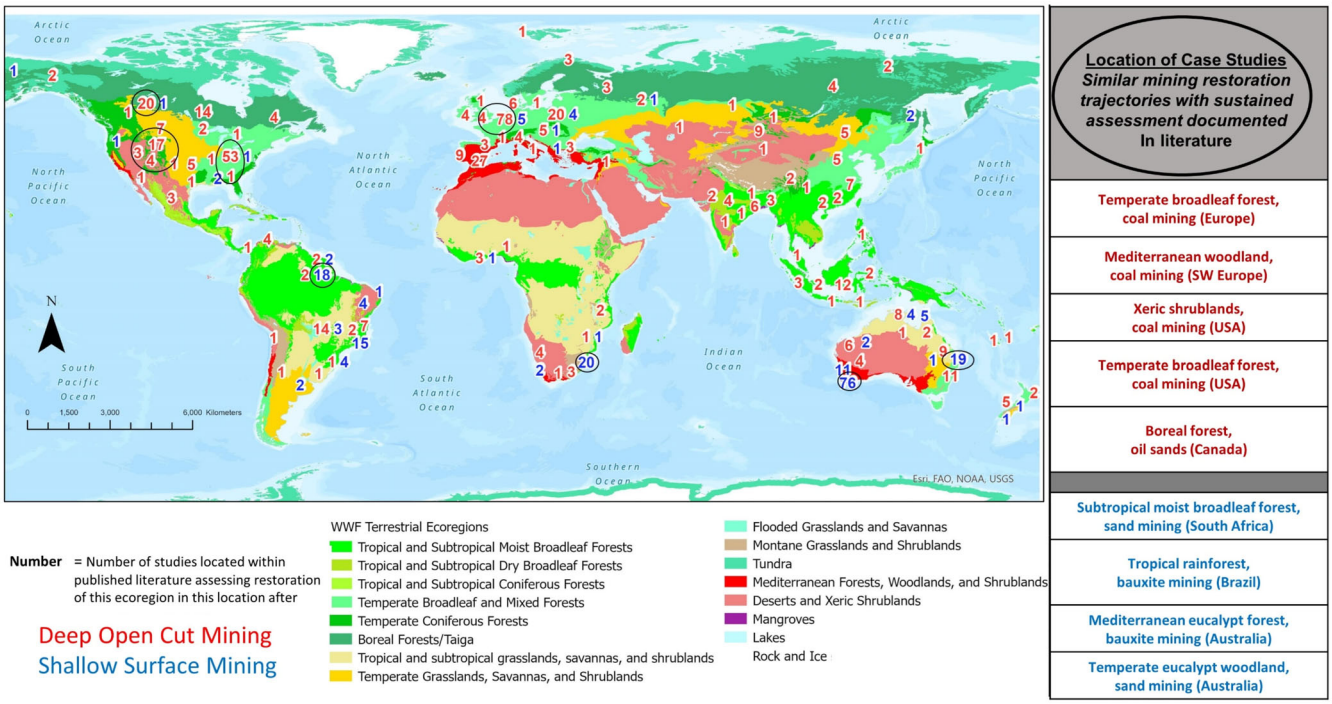

Figure 4. The number of reviewed studies assessing native ecosystem restoration after deep open cut (red numbers) and shallow surface (blue numbers) mining within different world ecoregions. Examples of locations where restoration trajectories (restoration of similar ecosystems restoring after similar mining) have had sustained assessment in literature are circled on the map and listed adjacent. The Terrestrial Ecosystem Map Layer is taken from World Wildlife Fund (Olson et al. 2001), and ecoregions are defined after Olson et al. (2001).

establishment patterns. Soil structure was also suggested to limit use of sites by fauna (e.g. Thompson & Thompson 2005; Larkin et al. 2008; Costa et al. 2010) but assessments linking measures of soil structure and fauna were rare (nine instances).

Assessments considering plant communities mostly involved measures of plant composition (species richness, diversity, community composition) or the structure of plant layers (canopy cover, shrub/ground cover, tree/shrub height, and biomass). Landscape scale patterns (e.g. change in vegetation cover over large areas indicated by remote sensing) were infrequently considered (54 instances) by studies assessing plants, although a trend of recently increasing assessment of landscape patterns was evident (Fig. 3A).

Consideration of ecosystem functions involving plants was mostly of recruitment involving assessment of dispersal to (recruitment into) sites inferred from changes in composition

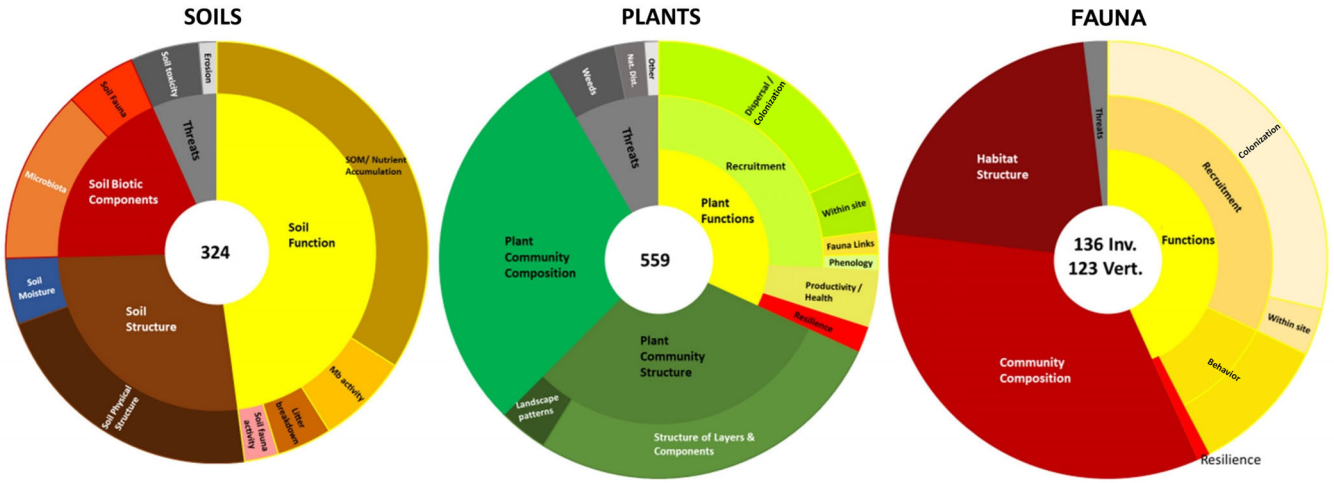

Figure 5. Mine restoration assessment literature wheels indicating proportional representation of the way different attributes of the composition, structure, functions, and threats of ecosystems restoring after mining has been considered by published studies using measures of soils, plants, and fauna.

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over time (272 instances). Consideration of whether established plants were reproducing from seed/vegetatively (recruitment within vs. into sites) was infrequent (67 instances). Other plant functions like flowering, pollination, and patterns of dispersal linked to fauna were rarely considered.

Of the few studies that considered resilience of restored plant communities to anticipated disturbances, most were of resilience of Mediterranean eucalypt forest to fire on the single operation case study from southwestern Australia (60% of 27 instances). Studies assessing threats to established plant communities that might derail restoration were relatively infrequent (22% of studies of plants) and mostly involved consideration of potential impacts of weeds (62% of 125 instances).

Studies that considered fauna usually assessed changes in numbers of species present with use, or colonization, of sites inferred from changes in species richness over time. Reproduction of fauna within restored areas was rarely considered (21 instances). Threats to animal populations within restored sites (11 instances), or resilience of fauna (e.g. whether they could recover from typical disturbances like fire) were very rarely considered (5 instances). Animal behavior was only considered as an indicator of restoration of natural functions in 62 instances and animal habitat was directly assessed in under a quarter of studies assessing fauna.

Restoration of ecosystem services was considered by only 47 studies, although all four categories of ecosystem services have been assessed for mining restoration (Fig. 6A). Most studies considering ecosystem services were published in the 5 years to 2021 (Fig. 3A). The most frequently assessed ecosystem services included "cultural values" of recreation and visual amenity pertaining to whether restoration of similarity in ecosystem composition and structure to surrounding natural areas was being achieved. Processes supporting valued habitats and regulating functions relating to storage of carbon, water quality, and soil conservation were also assessed. Provisioning services most frequently assessed were economic benefits (e.g. relating to employment) and timber resources.

Assessments of ecosystem services described involvement of community stakeholders in the undertaking of assessments in only two cases. Most documented assessments of ecosystem services on restoring mine sites were by researchers using inference (e.g. estimates of economic values from timber biomass) rather than assessments attempting direct measurement of ecosystem services (e.g. recreational values ascertained by surveys of recreational users) (Fig. 6B).

Case Studies of Similar Mining Restoration Trajectories with Sustained Published Assessment

Locations where mining restoration trajectories have had sustained study in the literature (Fig. 4; details in Table S5) include restoration of temperate broadleaf forest after coal mining in Western Europe and the United States. In Europe, publications include monitoring of sites that have undergone passive restoration for over 100 years, and of sites that have been actively restored in the past 50 years (Table S5). In two cases the identified case studies relate to single operations (rather than regional assessments). These include restoration of subtropical rainforest on sand dunes after sand mining in Richard's Bay, South Africa, and restoration of Mediterranean eucalypt forest after bauxite

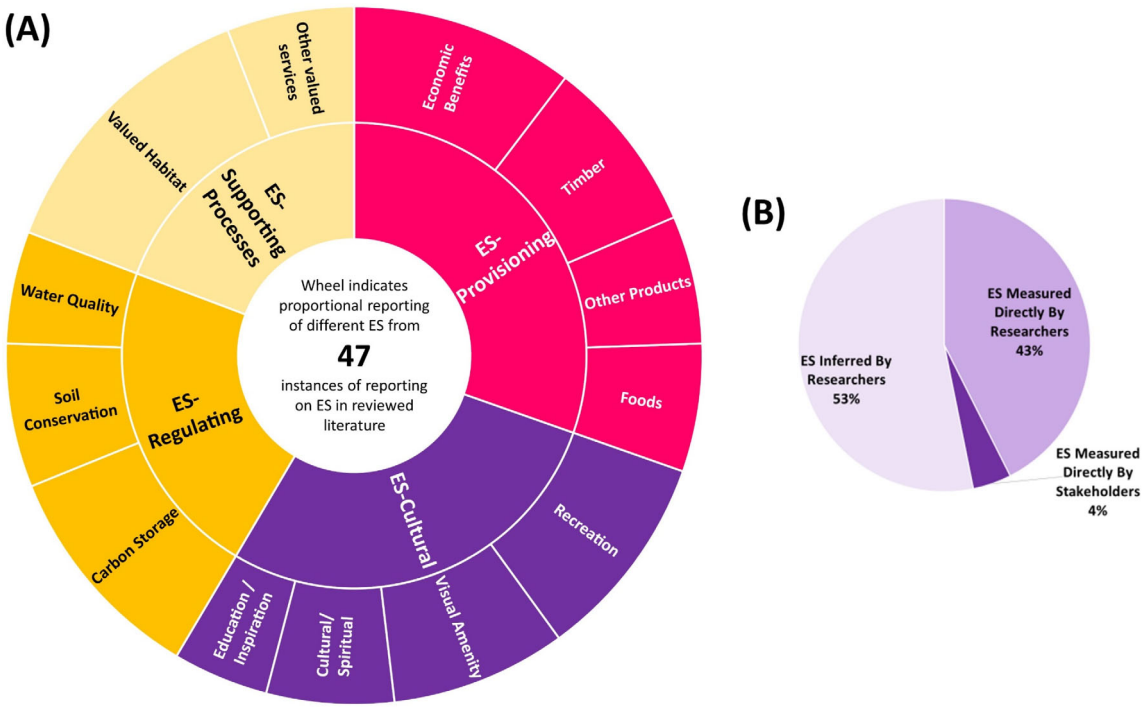

Figure 6. (A) Proportional representations of the ecosystem services assessed by reviewed studies and (B) methods used to determine them.

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mining, in Southwestern Australia (Table S5). Assessments relating to the latter contributed 36% of the reviewed shallow surface mining restoration studies. The instance of repeat surveys of active restoration documented for the case studies (and the two single operation cases in particular) contrasts with most assessments (in the entire assessment literature) that mostly used space-for-time inference to describe patterns with restoration age.

Figure 7 illustrates how collation of data from multiple studies can contribute "multiple lines of evidence" which might improve understanding of typical mine restoration trajectories. Reporting of indicators of sustainability in case studies (Fig. 7) suggests that the example from southwestern Australia is the only example of long-term restoration assessment in the published literature where resilience to an anticipated natural disturbance (fire) has been substantially assessed and considered for both flora and fauna. While recruitment of plants and fauna has been considered by assessments within all case studies, this has mostly involved inferences about dispersal into sites from changes in species composition over time. Even for these better studied trajectories, whether established plants are able to recruit (e.g. produce seeds that can establish on mine site soils) is infrequently assessed, and whether fauna are able to reproduce within sites (e.g. whether nesting habitat is available) is rarely considered. Reporting of soil invertebrate fauna composition and indicators of biotic interactions to suggest restoration of soil functions was most extensive in assessments of restoration of temperate broadleaf forest after coal mining in Europe (Fig. 7). In this case study, typical stages of mine restoration where improving soil quality is linked to development of soil fauna populations have been described (e.g. Frouz et al. 2008).

Table 1 indicates how the case study assessments have used reference sites and characterization of typical restoration stages (i.e. precedence) as aids in interpreting restoration progress on mine sites. Measures within native ecosystem reference sites were used for all cases, but relatively less commonly used in studies of European temperate broadleaf forests. Understanding of typical patterns of "succession" in temperate broadleaf forests and extensive study of chronosequences and repeat surveys has allowed authors to characterize typical stages along mining restoration trajectories of this type (Table 1). Description of typical restoration stages has also been possible for the southwestern Australia case study, where multiple chronosequences and repeat studied sites have been assessed for a single operation. A state and transition model describing typical restoration patterns has been used to suggest desired trajectories (i.e. to target end states), and justify compliance with mine closure criteria (Grant 2006).

The factors used across the case studies to suggest that restoration is on a desired trajectory are summarized in Table 2. Trends of increasing similarity to reference sites (especially in biodiversity measures) and evidence of plant recruitment are

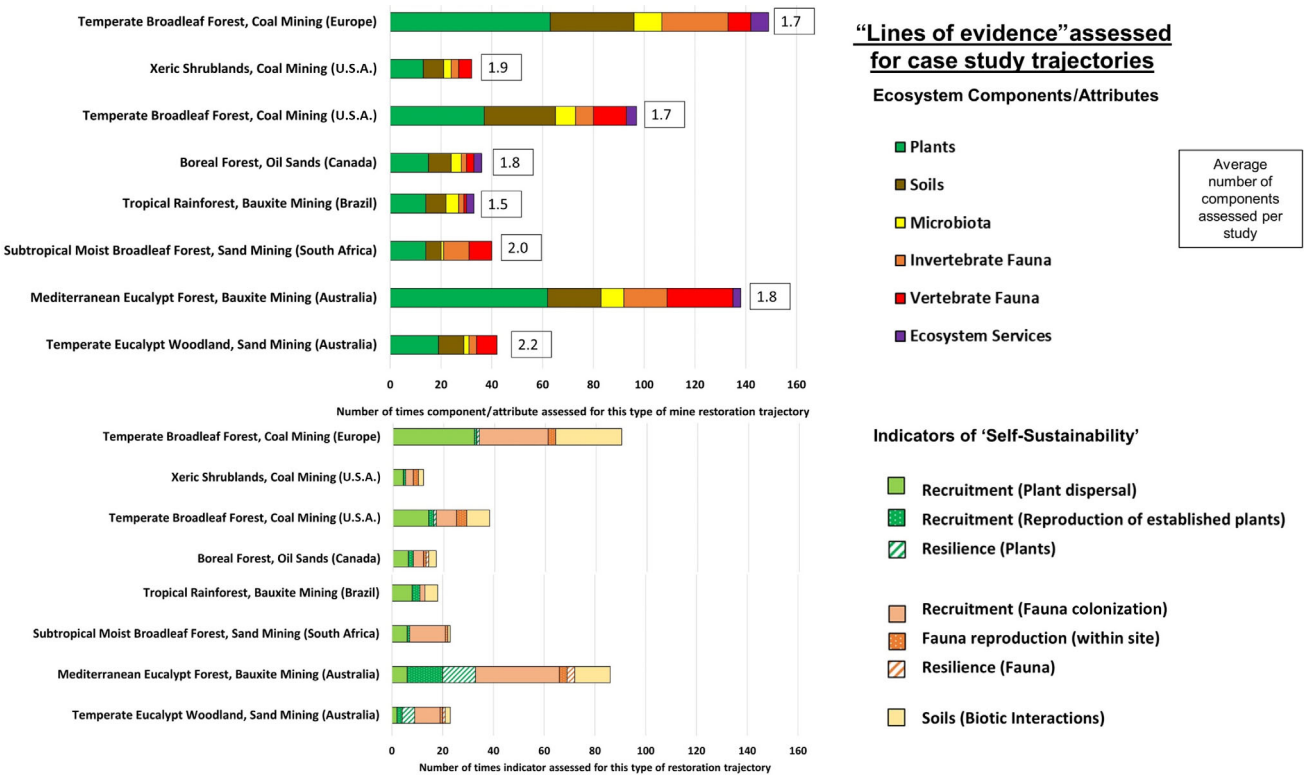

Figure 7. "Lines of evidence" (components/attributes and sustainability indicators) cumulatively assessed by the identified case studies of mining restoration trajectories with sustained study.

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Table 1. Factors informing understanding of restoration trajectories in case study assessments (refer to Table S6 for references in table).

	Measures in Reference Sites?			*Typical Stages of Development Described from Precedence or Informed by Native Ecosystem Disturbance Recovery?*		
		Types of Reference Sites				
Mine Restoration Literature Case Studies (Number of Studies Located by Review)	*% Studies with Reference Sites*	*Undisturbed Ecosystems*	*Ecosystems Recovering from Other Disturbance*	*Patterns of Disturbance Recovery in Native Ecosystems Referenced?*	*Mining Trajectory Stages Described?*	*Detail*
Temperate Broadleaf Forest, Coal Mining (Europe) (82)	37	X		X—"Typical" forest succession	Yes	Vegetation trajectory states: typical vegetation community trajectories toward "mature" forest frequently referenced as evidence of desired trajectories using chronosequences and repeat surveys (e.g. Lukešová & Komárek 1987; Prach & Pysek 1994; Wiegleb & Felinks 2001). Models of typical trajectory states post mining described using precedence (typical post mining patterns) and patterns of "succession" after other disturbances in natural forest by Prach et al. (2002) and Mudrák et al. (2016). Trajectories for soils and soil fauna also described from precedence (e.g. Tajovsky 2001; Dunger & Voigtlander 2005, Frouz et al. 2008; Madej et al. 2011) including threshold transitions in soil formation linked to development of soil fauna communities (e.g. Frouz & Nováková 2005; Frouz et al. 2008).
Xeric Shrublands, Coal Mining (U.S.A.) (17)	71	X			No	Trends of similarity with reference sites in vegetation composition and wildlife usage suggest desired trajectories and some precedence (similarity of restoration pattern in numerous sites) is described (e.g. Anderson et al. 2008). However, typical stages/models of trajectories are not described.
Temperate Broadleaf Forest, Coal Mining (U.S.A.) (54)	70	X	X—Logging/ Fire	X—Post-logging/ Fire recovery patterns and typical forest succession	No	Similarities of recovery patterns to post logging/fire disturbance discussed and colonization by "climax" species suggests progression toward desired ecosystem. However, typical stages/models of trajectories are not described.
Boreal Forest, Oil Sands (Canada) (18)	83	X	X—Logging/ Fire/ Clearing	X—Post-logging/ Fire/ Clearing recovery patterns	No	Trajectory understanding developed from long-term study of diverse parameters on previously mined surfaces including long-term field trials, permanent monitoring sites, and collation of research at different sites by an independent research agency (May et al. 2011). Patterns of recovery compared to recovery from other disturbances which suggests slower recovery on recreated substrates (e.g. Hawkes & Gerwing 2019). However, typical stages/models of trajectories are not described.
Subtropical Moist Broadleaf Forest, Sand Mining (South Africa) (20)	90	X			No	Trajectory understanding informed by patterns of increasing similarity to undisturbed forest sites for multiple parameters using chronosequences and longitudinal surveys. However, typical stages/models of trajectories are not described.
	80	X			No	

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Table 1. Continued

Mine Restoration Literature Case Studies (Number of Studies Located by Review)	Measures in Reference Sites?			Typical Stages of Development Described from Precedence or Informed by Native Ecosystem Disturbance Recovery?		
		Types of Reference Sites				
	% Studies with Reference Sites	Undisturbed Ecosystems	Ecosystems Recovering from Other Disturbance	Patterns of Disturbance Recovery in Native Ecosystems Referenced?	Mining Trajectory Stages Described?	Detail
Tropical Rainforest, Bauxite Mining (Brazil) (20)				X—"Typical" forest succession		Typical post-disturbance patterns in target rainforest including concepts of "pioneer" and "climax" species used to interpret trajectory patterns on mined areas. However, typical stages/models of trajectories are not described.
Mediterranean Eucalypt Forest, Bauxite Mining (Australia) (76)	93	X			Yes	Understanding of trajectories informed by sustained restoration monitoring using both chronosequences and longitudinal resurvey encompassing multiple sites. State and transition model developed (Grant 2006) describing states along trajectory toward end states required by closure criteria (e.g. defined species richness, cover, tree density). Model also describes likely undesired states, transitions between states and management methods to correct undesired trajectories.
Temperate Eucalypt Woodland, Sand Mining (Australia) (19)	84	X	X—Logging/Fire	X—Post Logging/Fire recovery patterns	No	Trajectory understanding informed mostly from trends of similarity toward reference sites. However, limited longitudinal survey documented, and typical stages/models of trajectories are not described.

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Table 2. Methods and indicators suggesting desired trajectories might be projected from assessments within case studies (refer to Table S6 for references in table).

Mine Restoration Literature Case Studies	*Ages When Projections of Desired Trajectories Suggested*	*Methods and Indicators Suggesting Development of Desirable Restoration Trajectories*					
		Trends of Similarity in Measures Toward Reference Values	*Development Along Anticipated Stages*	*Recruitment*	*Habitat*	*Resilience*	*Sustained Monitoring*
Temperate Broadleaf Forest, Coal Mining (Europe)	30–40 yr; active and passive	Soil fauna composition, activity and levels of soil organic matter (SOM)/nutrients (e.g. Frouz et al. 2015; Šebelíková et al. 2019)	Species composition matching typical stages of trajectories toward "mature forest" (e.g. references in Table 3)	Recruitment of native trees/shrubs to/and within sites suggests desired trajectory early (e.g. Bejcek & Stanstny, 1984; Haigh et al. 2020) Recruitment of "forest specialists" (e.g. Jagodziński et al. 2018; Šebelíková et al. 2019)	Use by native fauna (e.g. Bejcek & Stanstny 1984; Haigh et al. 2020)		Earlier projection of desired trajectories with long-term monitoring (e.g. Haigh et al. 2020)
Xeric Shrublands, Coal Mining (U.S.A.)	15–60 yr active; no successful passive described	Vegetation composition and wildlife usage (e.g. Anderson et al. 2008)		Early predictions of success with recruitment of native trees/shrubs (e.g. Francis et al. 1991; Wood et al. 1995; Petersen et al. 2016)	Development of targeted grazing habitat for large wildlife (e.g. Francis et al. 1991; Wood et al. 1995; Petersen et al. 2016)		Long-term monitoring of wildlife use including monitoring over life of mine (e.g. Petersen et al. 2016)
Temperate Broadleaf Forest, Coal Mining (U.S.A.)	30–40 yr active; 75+ yr passive	Plant species composition, tree structure, and SOM/nutrient levels (e.g. Carter & Ungar 2002; Copenheaver et al. 2006)		Colonization of characteristic trees/shrub seedlings and similar seedbank composition (e.g. Carter & Ungar 2002; Copenheaver et al. 2006)	Colonization by reference site soil fauna, birds, and mammals (e.g. Watters et al. 2005)		
Boreal Forest, Oil Sands (Canada)	30+ yr active; no successful passive described	Plant, bird, mammal, reptile, and amphibian richness and composition +		Colonization and reproduction on site of native plants including			Long-term monitoring of vegetation and fauna

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Table 2. Continued

Mine Restoration Literature Case Studies	*Ages When Projections of Desired Trajectories Suggested*	*Methods and Indicators Suggesting Development of Desirable Restoration Trajectories*					
		Trends of Similarity in Measures Toward Reference Values	*Development Along Anticipated Stages*	*Recruitment*	*Habitat*	*Resilience*	*Sustained Monitoring*
		soil nutrient levels (e.g. May et al. 2011; Hawkes & Gerwing 2019)		traditional use plants (e.g. May et al. 2011; Hawkes & Gerwing 2019)			communities (e.g. May et al. 2011; Hawkes & Gerwing 2019)
Subtropical Moist Broadleaf Forest, Sand Mining (South Africa)	35+ yr active; 150+ yr passive	Plants, soil fauna, and vertebrates (e.g. Rolo et al. 2016)		Colonization and growth of rainforest trees/ shrubs (e.g. Redi et al. 2005; Rolo et al. 2016)			Congruence of patterns in chronosequences and repeat surveyed sites (e.g. Rolo et al. 2016)
Tropical Rainforest, Bauxite Mining (Brazil)	40+ yr active; no successful passive described	Plant composition (e.g. Parrotta et al. 1997; Miranda Neto et al. 2014)	Establishment of characteristic plants including "climax" species typical of "mature forest" (e.g. Parrotta et al. 1997; Miranda Neto et al. 2014)	Recruitment of plants with different dispersal traits and especially faunal (e.g. Parrotta et al. 1997; Miranda Neto et al. 2014)	Visitation by fauna dispersers an early indicator of desired trajectories (e.g. Miranda Neto et al. 2014; Martins et al. 2021)		
Mediterranean Eucalypt Forest, Bauxite Mining (Australia)	15+ yr active; no successful passive described	Plant composition, birds, mammals, invertebrates, nutrient accumulation, and other indicators of "nutrient cycling" (e.g. summary in Koch & Hobbs 2007)	Early confidence in desired trajectory with establishment of structural and floristic states of model (Grant 2006; Grant et al. 2007)	Similar seedbank and seedling composition and growth to reference sites (e.g. Orozco-Aceves et al. 2017)		Studies demonstrating plant, fauna, and "soil function" resilience to fire for sites >15–20 yr (e.g. Morley et al. 2004; Grant et al. 2007; Craig et al. 2010)	Confidence in desired trajectory from 15 yr considering evidence from multiple studies (e.g. Koch & Hobbs 2007; Grant & Koch 2007; Orozco-Aceves et al. 2017)
Temperate Eucalypt Woodland, Sand Mining (Australia)	25+ yr active; no successful passive described	Plant diversity (e.g. Ross et al. 2004)		Similarity in metrics linked to recruitment (e.g. seedbank emergence; Ross et al. 2004)		Evidence of resilience in plants post-fire responses (e.g. Ross et al. 2004)	

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used as supporting evidence in all case studies. Development of habitat for fauna and evidence of resilience to typical disturbances were used as evidence of desired trajectories in the few studies where these were considered (Table 2). Sustained monitoring that includes repeat sampling over time and highlighting congruence between repeat measures and chronosequence patterns, gives assessors confidence that mine restoration is developing desired characteristics of native ecosystems (Table 2). Due to the limited reporting of indicators of "self-sustainability" revealed by our review we propose some examples of indicators that might demonstrate "self-sustainability" within regulatory time frames (Table 3).

Discussion

Breadth and Complexity of Mine Restoration Assessment Documented in the Literature

Documentation of Restoration Trajectories over Space and Time. This review found that restoration of native ecosystems after mining has been described in published literature for a variety of native ecosystems around the world, including examples of sustained documentation of recovery trajectories of comparable restoration. However, our review has highlighted a general paucity of long-term studies across multiple ecosystems, geographic locations, and mine types. As such, understanding of long-term restoration trajectories following mining is largely limited to assessment of a couple of single operations that have sustained monitoring of multiple indicators, using reference sites as a point of comparison. In other long-term assessments, conclusions about whether restoration efforts are on a desired trajectory are predominantly made by building up multiple lines of evidence across different restoration assessments.

Regions with long-term monitoring and reporting of similar mining restoration in literature were concentrated in Australia, Western Europe, Brazil, and North America. Concentration of mining rehabilitation research ("rehabilitation" includes sites not targeting native ecosystems) in these regions has been documented by previous literature reviews (e.g. Bruno Rocha Martins et al. 2020; McKenna et al. 2020). This may be linked to well-resourced mine research centers which have developed in regions with large resource industries (Bruno Rocha Martins et al. 2020). The advantages of long-term partnerships between research institutions and mining companies in fostering quality restoration research has been documented (Rokich 2016).

A recent trend of more published assessments considering a greater variety of ecosystems suggests that understanding of post-mining restoration trajectories in other ecosystems is emerging. It is likely, and desirable, that the publication of more detailed and comprehensive accounts of mine restoration assessment will increase and accelerate as more large mined areas move into phases of closure within the next decade (Brock 2020), and with increasing expectations that restoration will lead to self-sustaining, resilient native ecosystems (Young et al. 2022).

The case studies illustrate how collation of data from multiple studies can contribute to our understanding of the expected trajectory of similar types of mine restoration projects, including the different drivers and indicators that help illustrate restoration progress and success. For example, the southwestern Australia bauxite restoration illustrates how formalizing this understanding within a conceptual state and transition model can help illustrate projections of desirable trajectories, and directly link monitoring indicators with the mine closure criteria.

Collaboration between companies and research organizations can facilitate publication of monitoring and the availability of data, thus helping to improve both the understanding of expected restoration trajectories, and the practice of assessing mine restoration projects. Such regional collaboration has occurred for the oil sands mining industry in Alberta, Canada, where focus has been directed to documenting and preventing cumulative mining impacts (Spaling et al. 2000). Some recent efforts have emerged that aim to enhance understanding of mine restoration trajectories by collating unpublished research (e.g. Shackelford et al. 2018; Hernandez-Santin et al. 2020), and it is likely that many more mining regions could draw on substantial unpublished "gray literature" within mining company databases to accompany published assessments. This could be facilitated by instigating requirements for companies to publish site assessments, or at least to make results publicly accessible.

Overall resurvey of sites and establishing long-term monitoring plots to indicate trends over time should be prioritized, because (as illustrated by our case studies) demonstrating desirable trends (e.g. species composition becoming more similar to reference sites) is required for projecting with confidence that restoration is on a trajectory toward a desired endpoint. Trends, and understanding of trajectory drivers, cannot necessarily be inferred from space-for-time data.

Components and Attributes Assessed. Especially in the last 5 years, there has been substantial increase in the breadth and complexity of assessment of mine restoration in terms of what ecosystem components and attributes are assessed. Increases in some areas of focus, and an ability to measure different components, in part reflect application of new technologies. A recent increase in the number of publications considering soil microbiota and landscape scale vegetation patterns follows advances in soil DNA analysis and remote sensing that allow new approaches and insights for restoration assessment (e.g. van der Heyde et al. 2020; Loewensteiner et al. 2021). Increased use of satellite or drone-based sensors, as documented in other recent reviews of rehabilitation literature, may provide more scope for landscape scale measures of plant community structure and composition in mine restoration assessments and might demonstrate goals of similarity and blending with adjacent ecosystems at landscape scales (Bruno Rocha Martins et al. 2020; McKenna et al. 2020; Rudge et al. 2022).

An apparent recent trend of an increase in study of vertebrate fauna is interesting considering previous documentation of only limited consideration of vertebrate fauna in mine rehabilitation assessments (Cross et al. 2019). It might be that vertebrate fauna were relatively more often considered in the studies collated here

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Table 3. Limitations and potential improvements for indicators of "self-sustainability" described in mine restoration literature (refer to Table S6 for references in table).

"Self-Sustainability" Indicators	*Use in Literature*	*Comments/Limitations*	*Potential Measures/Tools for Better Assessment*
Trends of increasing composition similarity	Trends of similarity in plant (and less frequently fauna) composition are frequently reported as indicators of desirable trajectories.	Increasing similarity in species presence and abundances should indicate site suitability and support projections of desirable trajectories. However, • Trends require long-term repeat monitoring and early trends may reverse (e.g. if sites lack conditions for recruitment or resilience). • Species characteristic of "mature" ecosystem (e.g. hollow dependent fauna) or sensitive to site constraints (e.g. hard soils) may be slow/unable to colonize.	• Long-term repeat monitoring incorporating testing of resilience. • Identifying indicator species (e.g. species absent from sites with poor soils, species characteristic of "mature" ecosystems, or fauna important in processes) to provide early indication of desirable/undesirable trajectories and suggest management actions.
Plant and Animal Recruitment	• 38% studies assessed plant recruitment and recruitment by "framework"/"later stage" species suggests restoration success early (Table 2). But only 20% of recruitment studies assessed reproduction from established plants. Also, poor recruitment of shrubs/trees indicates deviated trajectories for all open cut mine restoration case studies inked to unsuitable substrates (e.g. Gibson et al. 1985; Pietsch 1996; Frouz et al. 2001; Olson et al. 2001; Rinella et al. 2015) • Reporting on fauna habitat is relatively uncommon and consideration of whether habitat permits reproduction rare.	Reproduction of established plants and provision of habitat supporting fauna reproduction (or at least confidence that there are no barriers to this occurring) is necessary to demonstrate "self-sustainability." But reproductive maturity/development of habitat may be slow and reproduction may be episodic.	• Describing typical stages including patterns of recruitment of plant types ± when recruitment is resilient with tools like state and transition models informed by data from existing sites and reference ecosystems might indicate desirable trajectories early and suggest management interventions. • Indicators suggesting absence of barriers to recruitment (e.g. demonstrating potential for establishment of plants from seed [or other typical regeneration pathway], similarity in seedbanks, resilience of recruits to typical disturbances; evidence hollows will form or denning animals can use sites within reasonable time frames).
Indicators of restoration of "nutrient cycling" processes	• Patterns of accumulation of plant growth nutrients toward similarity with reference sites are frequently considered evidence of "restoration of cycling." • Increasing soil fauna diversity and microbial diversity + levels of soil fauna/microbiota activity (e.g. soil respiration) are assumed to indicate restoration of soil functions.	• Patterns of plant nutrient increase might indicate restoration of capacity to support further ecosystem development. However, in some cases levels might reflect overuse of fertilizers and undesirable trends. • Soil fauna composition and activity might reflect desirable soil formation trajectories (e.g. Frouz et al. 2008) yet study of soils and fauna over time required for linkages are rare. • Measures reflecting overall abundance or activity of soil organisms may not reflect	Indicators measuring biota or activity necessary for processes of nutrient cycling may better indicate restoration of processes. This requires documenting relationships between soils and biota over time. Measures might include documenting developing similarity in indicator species of soil microbiota or decomposer fauna linked to particular functions or that are sensitive to factors on mine sites (e.g. termites and ant species which build mounds) or are known to have a significant role in breaking

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Table 3. Continued

"Self-Sustainability" Indicators	*Use in Literature*	*Comments/Limitations*	*Potential Measures/Tools for Better Assessment*
		restoration of specific functions.	down leaf litter (e.g. microbiota with roles in key nutrient cycling processes).
Absence of limiting factors/ threats	• Soil chemistry that might impact plant or soil biota was infrequently described in mine restoration literature. • Soil depth and hardness compared to reference ecosystems has been assessed for mine sites using measures like bulk density and penetration resistance with similarity trends toward measures in reference soils considered desirable.	• Undesirable trajectories are often linked to poor substrates limiting establishment of plants and hard substrates are also suggested as limiting for fossorial fauna. Yet few studies directly measured links between soil condition and plants and no located studies linked soil condition with fauna. • Measures at older sites suggest residual toxicity may have long-term impact on soil micro biotic communities and functions.	Indicators suggesting an absence of barriers to restoration of processes/habitat may provide confidence that sites will develop desired function and habitat (e.g. recruitment as above, absence of soil physical conditions and chemistry that are limiting to soil fauna).
Resilience to anticipated disturbances	Mine restoration literature considering resilience is mostly confined to studies of plant community recovery after fire in the Australian bauxite restoration case study. Comparisons of post-fire plant recovery and recruiting, soil nutrients and fuel loads in restored and reference sites suggested fire exclusion and Acacia thinning were necessary in sites younger than approximately 15 yr	Resilience to natural disturbances in ecosystems adapted to fire or other disturbances might require time to develop with early exposure preventing restoration progress. Few studies of resilience to disturbances other than fire.	For ecosystems where fire and other natural disturbances (e.g. flooding) are likely a program of assessment of resilience (e.g. experimental imposition of disturbance types, or imposition of monitoring to assess impacts of unplanned disturbance) might be developed for older restoring sites with before and after monitoring of disturbance impacts to test areas and reference sites. Recovery of mature plants, plant recruitment impacts (seedbanks, seedlings), soil functioning, and impacts on fauna might be assessed.

because they were focused on sites restoring native ecosystems, rather than less ambitious mine rehabilitation. Notwithstanding this apparent recent increase, there are disproportionately few assessments of fauna in the studies we collated, and especially so in relation to ecosystem functions. With the importance of fauna in influencing successful restoration through involvement in important processes like plant recruitment and nutrient cycling, more consideration of fauna (perhaps requiring regulation around assessments) is warranted (Cristescu et al. 2012; Catterall 2018; Cross et al. 2019).

Trends and Gaps in Mine Restoration Assessment Practice

Published mine restoration assessments have focused on indicators of similarity using structural and compositional attributes, rather than indicators relating to restoration of ecosystem functions. This may be because many simple measures of composition (e.g. species richness) and structure (e.g. canopy cover) may be relatively easily assessed in single assessments and can reach similarity to measures in a reference ecosystem relatively quickly. As such a focus on these types of indicators might reflect a tendency for assessments to focus on "leading" (evident early in trajectories) rather than "lagging" (only evident in more mature restoration) indicators of restoration trajectories (sensu Manero et al. 2020) because these might more readily demonstrate desired restoration outcomes for mine closure decisions.

While structural similarity to reference ecosystems might occur quickly for commonly used measures (like tree density or shrub cover for forests), this is not necessarily a surrogate for other restoration progress and must be measured and interpreted carefully. Initial assessments of early restoration stages using simple structural metrics (e.g. overall tree density/cover) do not necessarily imply that progression toward mature restoration will occur (e.g. compositional similarity).

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Early assessments of restoration of rainforest in Richard's Bay, South Africa, after sand mining suggested that structural attributes (cover) were progressing toward similarity with the reference state, but this convergence later reversed, as did trends in fauna and plant species diversity, as an initial canopy of Acacia senesced and was slowly replaced by growth of longer lived rainforest (Rolo et al. 2016). Acacia had been considered "arresting" of recovery trajectories of this ecosystem more broadly (i.e. restoration after mine and nonmining disturbance) possibly by preventing establishment of rainforest trees due to shading and impacts on nutrient cycling (Boyes et al. 2009, 2011). However, an accompanying study suggested that "arrested succession" in restoration of this ecosystem might occur due to grazing preventing seedling growth, which highlights the importance of considering both interactions with fauna, and the need for assessment of restoration trajectories over longer periods (Boyes et al. 2009).

Some recent studies have used analysis of structural metrics to highlight disparity between restoration progress and mining goals of self-sustaining similar ecosystems when considering restoration projects across larger scales. For example, modeling of size class distributions of different woody species have been used to project outcomes of restoration of eucalypt forests on former coal mines in Australia, highlighting concerns that an initial dominance by short-lived Acacia and limited evidence of recruitment of longer-lived eucalypts may not result in a "self-sustaining" eucalypt forest (Ngugi et al. 2015). An assessment of multiple restored Appalachian coal mines that used satellite imagery to explore plant community structural similarity over large scales and long time frames similarly highlighted the potential for poor overall outcomes, which may be less apparent at smaller scales (e.g. Ruggles et al. 2021). Both examples highlight the critical importance of monitoring that is able to demonstrate success at appropriate spatial scales.

Our review suggests that assessment of ecosystem function on mine sites has generally been via inference rather than on more direct investigation of whether functions are occurring in a similar or desired way. For soils, restoration of "nutrient cycling" is mostly inferred from changes in accumulation of soil organic matter or carbon and plant macronutrients, rather than from assessments investigating biotic interactions necessary for nutrient cycling processes. A pattern of increasing similarity to reference sites using measures of soil carbon and macronutrients may be readily demonstrated with simple soil testing. However, several examples suggest this may not reflect restoration of nutrient cycling functions as rapid accumulation of soil macronutrients (and in some situations nonlinear trajectories with higher levels of macronutrients in restored sites in early restoration) may be due to use of fertilizers, unnatural technosols, weed cover, or dense cover of nitrogen fixers, which has been linked to poor restoration outcomes (e.g. Silva et al. 2013; Masse et al. 2017; Tibbett et al. 2019; Daws et al. 2021). Assessments of whether biotic interactions necessary for restoration of nutrient cycling are occurring may provide a better indication of the progress of restoration of desired processes. However, this may be challenging, especially where these processes in native ecosystems are not well understood. Nonetheless, links between soil fauna population changes and soil development toward conditions that occur in natural soils have been made for mine restoration trajectories that have been studied over long periods (e.g. Frouz et al. 2006; Frouz et al. 2008). Applying soil genomic techniques to demonstration of functions involving microbiota might be an area of focus that could improve understanding of trajectories of soil functions (Bastida & Jehmlich 2016) and there are recent examples of this in assessment literature (e.g. van der Heyde et al. 2020; Bizuti et al. 2022). However, to suggest restoration of function, measures would need to reflect restoration of particular interactions rather than simply increases in microbiota diversity or general microbial function (e.g. total soil respiration).

Assessment of Ecosystem Self-Sustainability

Despite the commonly expressed goal that mine restoration will be self-sustaining, we found relatively few assessments considered relevant indicators, like recruitment, absence of threats, and resilience to disturbances. This may reflect the fact that many sustainability processes might develop beyond the time frame associated with most monitoring programs (see Kragt et al. 2019). It might also suggest that closure criteria with goals of "self-sustaining" ecosystems are not adequately linked to specific assessment like measures of recruitment. Demonstrating adequate recruitment of characteristic flora and fauna is a shorter-term measure that is particularly important in demonstrating that established conditions are able to support a "similar" and self-sustaining desired native ecosystem. In this review, plant recruitment was used to project desirable trajectories in all case studies, and low recruitment (of woody plants) was used an indicator of poor outcomes, especially in open cut mining sites. However, most measures of recruitment in literature (even for the case studies) involved inferences from colonization of sites rather than measures of reproduction by established plants. Documenting recruitment of important plants, including species that are characteristic of mature ecosystems, was noted as a leading indicator (evident early in the trajectory) that conditions suitable for desired species had been established in some case studies. However, confidence in achieving sustainability of restoration requires documenting development of reproductive success within sites (or at least an absence of barriers to this). Impacts on recruitment can be subtle and require targeted study that considers both plants and fauna and their interactions. Yet recruitment of fauna within sites is rarely reported.

The focus of the assessed literature suggests that there have been relatively few assessments of resilience to anticipated natural disturbances and other threats on mine sites, with the exception of studies exploring recovery following fire in eucalypt forests established on a few Australian mine sites. Again, the resilience of fauna communities to disturbance was virtually unstudied. This is not particular to mining restoration, as assessments of resilience is not common in landscape restoration projects more broadly (Cowan et al. 2021).

Due to the difficulties in assessing and concluding resilience has been achieved in mine restoration projects, adaptive

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management trials may be required. Incorporating resilience testing into restoration monitoring may both provide confidence in desired trajectories, and improve outcomes, such as occurred in burning trials in older temperate eucalypt forest restoration sites in eastern Australian where results suggest increased biodiversity in restoration could be promoted with the introduction of fire (McKenna et al. 2019). However, there are obvious threats beyond fire which need to be considered in monitoring, like the potential threats to biota from residual toxicity, and we found that reporting of these threats to future restoration was limited. This is despite toxicity being suggested as a problem in poor mine restoration, and for returning sites that can be safely used by people (e.g. Bennett 2016; Camizuli et al. 2018). Other limitations which might be considered "threats" to restoration progress, like hard or compacted soils, were often postulated as linked to poor outcomes, but assessments of these factors were rarely linked to restoration indicators like plant recruitment success.

Assessment of Ecosystem Services

Ecosystem services were rarely considered in mine restoration assessments published in recent decades (see also (Boldy et al. 2021), notwithstanding the commonly specified goals of restoration of productive uses and other social benefits for mine restoration. However, a focus on ecosystem services has been proposed as a means of achieving stakeholder agreement around mine closure (Rosa et al. 2020) and case studies of their consideration in restoration planning have recently been described (Rosa et al. 2019; Young et al. 2022). We documented an increase in use of indicators relating to restoring ecosystem services in mine restoration assessments published in the 5 years to 2021, perhaps suggesting increasing recognition of a need for consideration of social benefits from mine rehabilitation.

Nonetheless, our review also indicates that ecosystem services assessment in mine restoration literature has often been superficial and that assessments rarely directly involved impacted communities. Published assessments considering ecosystem services mostly involved researchers making indirect measures that involved inference that ecosystem services were developing (e.g. carbon storage inferred from tree biomass). There has been limited consideration of cultural values obtained from interviews, or other direct consideration and involvement of people. If mine restoration is to provide stakeholder benefits via life of mine involvement as recommended in the SER MSRS (Young et al. 2022), developing indicators and methods for assessments of social benefits, including facilitation of stakeholder led assessments, might be one area where mine restoration research could support achievement of mine restoration goals. Although restoration of ecosystem services develops with biophysical restoration, a focus on stakeholder objectives for restored sites, the rate of restoration of important services (e.g. reproduction of native food trees), and how cultural values that arise from participating in restoration (e.g. valuing of traditional knowledge) can be enhanced is important. This may be especially the case where timescales to relinquishment are long and cultural continuity requires site access and use of resources (e.g. Rosa et al. 2019). Assessments that are stakeholder led will likely facilitate confidence that restoration is developing desired end uses, and confidence that sites can be reincorporated into community management, at points of relinquishment.

Can We Better Assess Progress Toward Mine Restoration Goals?

This comprehensive review of mining restoration literature against commonly specified restoration goals suggests that, although there has been notable progress over time with the breadth and duration of mine restoration assessment, there are likely significant deficiencies in our ability to determine and predict the success of mine site restoration with our current assessment approaches. In particular, the mine restoration literature appears to inadequately assess factors necessary for demonstrating common goals of "self-sustaining" and "resilient" ecosystems. We contend that developing better indicators of "self-sustainability" requires attention and have proposed some examples of indicators that might demonstrate "self-sustainability" within regulatory time frames. Even if mine site restoration goals acknowledge limitations and aim for "functioning" natural ecosystems rather than similarity with reference sites (e.g. Doley & Audet 2016), "self-sustainability" still needs to be demonstrated. For indicators of processes like plant recruitment which may develop over long time frames, or be episodic, it might be necessary to demonstrate potential for sustainability using measures that can demonstrate an absence of barriers (like hard soils) to meet mine closure time frames. Many of the monitoring improvements we propose to better demonstrate "self-sustainability" on mine sites, such as identifying indicator species, require a sophisticated understanding of restoration trajectories and reference ecosystems. This further highlights the value of developing understanding of restoration trajectory patterns by establishing more long-term monitoring studies, and collating research and company assessments of similar restoration projects from the gray literature. Better assessment from long-term monitoring using indicators providing evidence of sustainability and resilience, as well as benefits desired by stakeholders using stakeholder-led assessment, are needed for confidence that mining can achieve commonly articulated socioecological restoration goals.

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Supporting Information

The following information may be found in the online version of this article:

Table S1. Examples illustrating how similar mine restoration goals have developed in different regions.
Table S2. Definitions of categories and other terms used to classify and describe restoration and assessments in the reviewed studies (and used within our literature review paper).
Table S3. Considered ecoregions: ecoregions restoring on mine sites considered by reviewed assessments.
Table S4. Extracted data: quantitative and qualitative data extracted from all studies included in review.
Table S5. Case studies detail: similar mining restoration trajectories with sustained assessment in literature.
Figure S1. Number of reviewed mine restoration assessments published within five-year periods to 2021.
Figure S2. Ore mined at restored sites assessed by reviewed literature within time periods.
Supplement S1. Further details of methods used to develop mine restoration assessment literature wheels.
Table S6. List of studies and assessed mine restorations within review.

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